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# SHOCK WAVES IN THE STUDY OF SHAPED CHARGES

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AUGUST 1991



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This report provides a basic description of the shaped charge concept, history of shaped charges, and various applications of shaped charges. In addition, three current research topics in the shaped charge field are presented.

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## 1. INTRODUCTION

A cylinder of explosive with a hollow cavity in one end and a detonator at the opposite end is known as a hollow charge. The hollow cavity, which may assume almost any geometric shape such as a hemisphere, a cone, or the like, causes the gaseous products formed from the initiation of the explosive at the end of the cylinder opposite the hollow cavity to focus the energy of the detonation products. The focusing of the detonation products creates an intense localized force. This concentrated force, when directed against a metal plate, is capable of creating a deeper cavity than a cylinder of explosive without a hollow cavity, even though more explosive is available in the latter case. This phenomenon is known in the U.S. and Britain as the *Munroe Effect* and in Europe as the *von Foerster* or *Neumann Effect*.

If the hollow cavity is lined with a thin layer of metal, glass, ceramic or the like, the liner forms a jet when the explosive charge is detonated. Upon initiation, a spherical wave propagates outward from the point of initiation. This high pressure shock wave moves at a very high velocity, typically around 8 km/s. As the detonation wave engulfs the lined cavity, the material is accelerated under the high detonation pressure, collapsing the cone. During this process, depicted in Figure 1 for a typical conical liner, the liner material is driven to very violent distortions over very short time intervals, at strain rates of $10^4$-$10^7$/s. The jet material undergoes elongations of 1,000 % or more. Maximum strains greater than 10 can be readily achieved since superimposed on the deformation are very large hydrodynamic pressures (peak pressures approximately 200 GPa, decaying to an average of approximately 20 GPa). The collapse of the conical liner material on the centerline forces a portion of the liner to flow in the form of a jet where the jet tip velocity can travel in excess of 10 km/s. Because of the presence of a velocity gradient, the jet will stretch until it fractures into a column of particles.

When this extremely energetic jet strikes a metal plate, a deep cavity is formed, exceeding that caused by a hollow charge without a liner. Peak pressures in the metal plate of 100-200 GPa are generated, decaying to an average of 10-20 GPa. Average temperatures of 20-50% of the melt temperature and average strains of 0.1 to 0.5 are common. Localized temperatures and strains at the jet tip can be even higher. The penetration process occurs at strain rates of $10^6$-$10^7$/s. The cavity produced in the metal plate due to this jet-target interaction is due not so much to a thermal effect but to the lateral displacement of armor by the tremendous pressures created (Figure 2). The target material is actually pushed aside and the penetration is accompanied by no change in target mass, neglecting any impact ejecta or spall from the rear surface of the target.

The cavity formed becomes deeper yet when the explosive charge containing the liner is removed some distance away from the plate. This distance, for which an optimum exists (Figure 3), is called the *standoff distance*. Devices of this nature are called *lined cavity charges* or *shaped charges*.

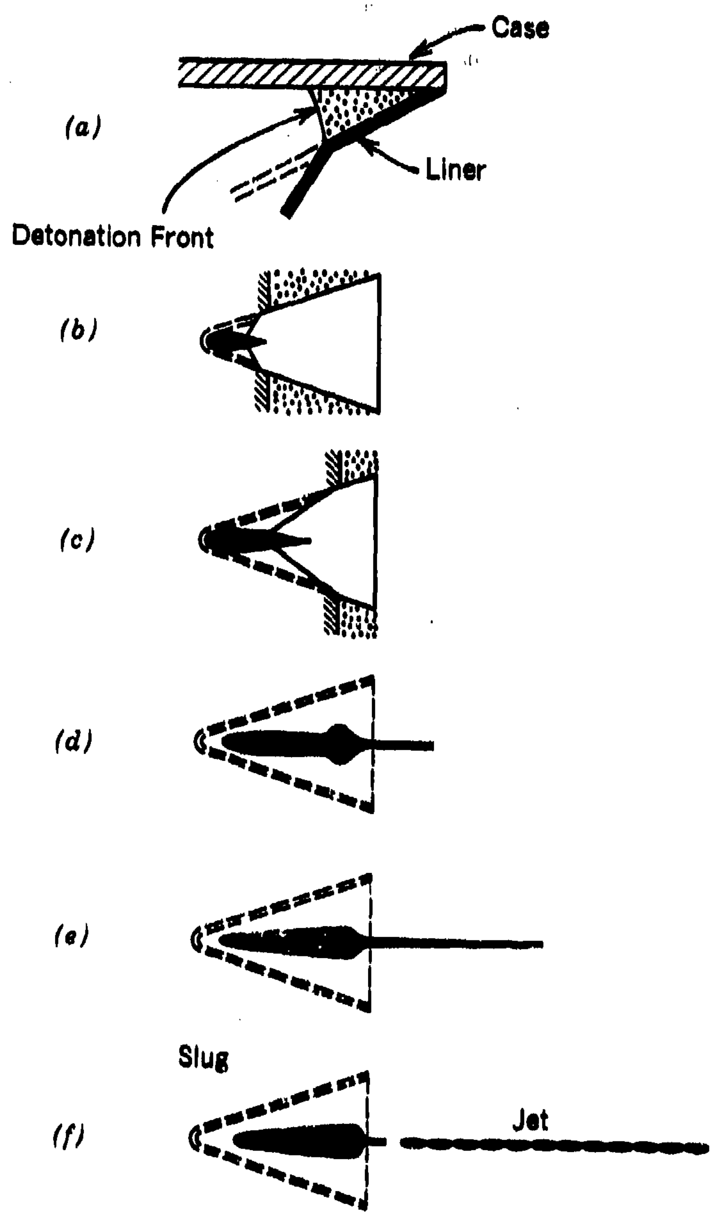



Figure 1. The Collapse of A Shaped Charge With A Conical Liner.

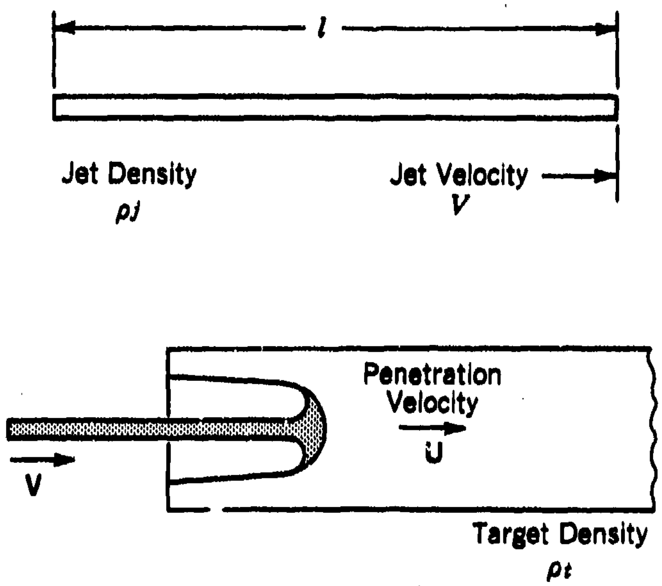



Figure 2. Jet Penetration.

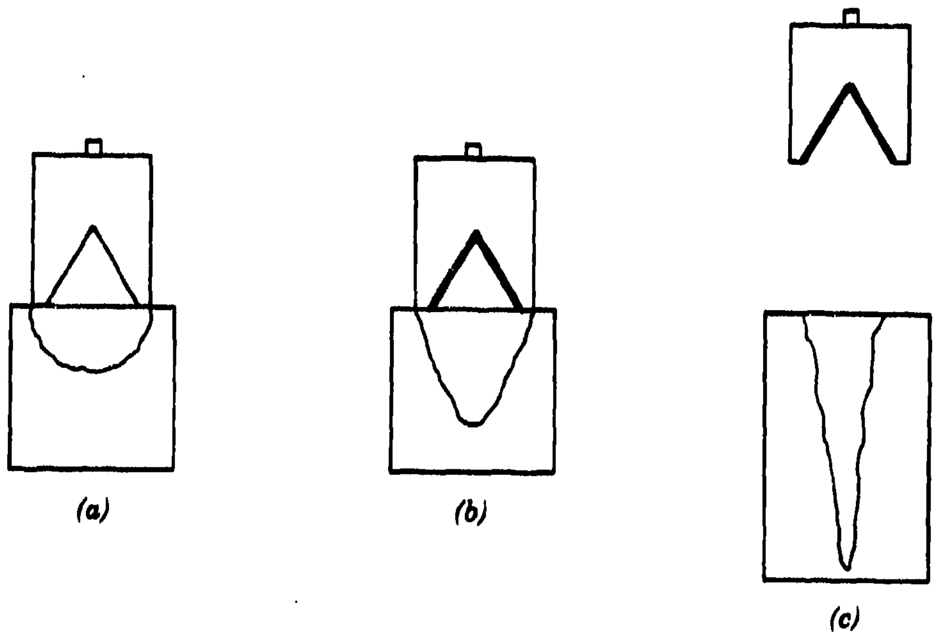



Figure 3. The Lined Cavity Effect.

The shaped charge concept is not well understood by people outside the technical community. For example, the jet from a shaped charge is not a "cutting plasma" nor does it burn its way through the metal target, as reported in many newspaper and even semi-technical journal articles.

Detailed discussions of the shaped charge concept and a complete list of sources (too numerous to list here) are available elsewhere (Walters and Zukas 1989; Zukas 1990; Walters 1991). The purpose of this paper is to highlight a few topics in modern shaped charge research, especially as related to the physics of shock waves.

## 2. A BRIEF HISTORY OF THE SHAPED CHARGE

The history of shaped charge conception and development is wrought with controversy. In 1792, the mining engineer, Franz von Baader (Walters and Zukas 1989) allegedly noted that one can focus the energy of an explosive blast on a small area by forming a hollow in the charge. However, von Baader used black powder in his experiments which is not capable of detonation or shock formation. Actual shaped charge devices were made possible by the discovery of blasting caps (detonators) by Alfred Nobel in 1867.

The first demonstration of the hollow cavity effect for high explosives was achieved by von Foerster, the true discoverer of the modern hollow charge, in 1883.

The hollow cavity (i.e., unlined shaped charge) was rediscovered by Charles E. Munroe of the Naval Torpedo Station, Newport, Rhode Island. Munroe's discoveries date from 1888 and are well documented.

Munroe detonated blocks of explosive in contact with steel plates. The explosive charge had the initials U.S.N. (United States Navy) inscribed on the charge opposite the point of initiation. These initials were reproduced on the steel plate. Munroe further observed that when a cavity was formed in a block of explosive, opposite the point of initiation, the penetration, or depth of the crater produced in the target, increased. In other words, a deeper cavity could be formed in a steel block using a smaller mass of explosive! (Earlier, von Foerster performed similar explosive engraving experiments.) The increase in penetration results from the focusing of the explosive gases (detonation products) by the hollow cavity.

One of the first lined shaped charges was devised by Munroe. This devise consisted of a tin can with sticks of dynamite tied around and on top of it, with the open end of the tin can pointing downward. It was used to punch a hole through the top of a steel safe.

Early German reference to the hollow cavity effect, after von Foerster, occurred in 1911-1912 patents in the U.K. and Germany. These patents clearly demonstrated the hollow cavity effect and the lined shaped charge effect.

Others attribute the hollow cavity effect to M. Sukharevskii (also transliterated as Sukhreski and Sucharewski). Indeed, Sukharevskii was the first known Soviet to investigate the shaped charge effect (in 1925-1926).

Early British development of the hollow cavity charge includes the achievements of Evans, Ubbelohde, Taylor, Tuck, Mott, Hill, Pack, and others.

In the U.S., the contributions of Watson on percussion fuzes and Wood on self-forging fragments (also called explosively formed penetrators, Misznay-Schardin devices, ballistic discs or P-charge projectiles) were significant.

The Watson percussion fuzes, patented in 1925, used a parabola-shaped booster charge with a metal lined hemispherical cavity to intensify the effect of the booster charge.

R. W. Wood of the Johns Hopkins University described what is known today as an explosively formed penetrator. Wood's studies originated during his investigation of the death of a young woman who, on opening the door of a house furnace, was killed by a small particle of metal which flew out of the fire and penetrated her breast bone. The small particle of metal was from the coned end of a detonator which was apparently delivered with the coal from the mine. Eichelberger (Walters and Zukas 1989) credited Wood for recognizing the enhancement obtained by metal lined hollow charges.

The lined cavity shaped charge research accelerated tremendously between 1935 and 1950 due primarily to World War II and the application of shaped charges to the bazooka, panzerfaust, and other devices. The history of shaped charge development during this time frame is somewhat ambiguous in that the British, Germans, and U.S. have all made significant claims to the early development of modern lined cavity charges.

The discoverers of the modern lined cavity effect were Franz Rudolf Thomanek for Germany and Henry Hans Mohaupt for the U.S.. Thomanek and Mohaupt independently perfected the hollow charge concept and developed the first effective lined cavity shaped charge penetrators.

Thomanek and colleagues suspected that overlapping shock waves from the jetting of a hollow charge formed a new, more intense shock wave from the superposition of two primary shock waves. Thus, tests were

performed with a glass lined, evacuated cavity to determine the optimal air cavity pressure. In 1938, Thomanek and Schardin observed that glass lined shaped charges revealed superior performance due to the glass liner and not due to the evacuated cavity. Further studies concluded that iron and copper liners were especially suitable for increasing penetration .

The hollow charge, or unlined shaped charge was first deployed on May 10, 1940 by the Germans on the Belgian fort of Eben Emael. The hollow charges knocked out the steel cupolas (6 inches thick) and observation turrets which lead to the early demise of the Belgian defenses (Zukas 1990; Walters 1991).

The Germans were also instrumental in transferring hollow charge research to the Japanese. There is no evidence of hollow charge research in Japan before May 1942. The Japanese anti-tank shells, although not as effective as those developed by the Germans or the Allies, were used effectively on the Burma front. Other Japanese innovations included the suicidal "Lunge" mine which was in fact a shaped charge with a wooden handle used as an anti-tank weapon.

The shaped charge principle was first clarified and understood as a result of the pioneering flash x-ray photographs taken in the U.S. by Seely and Clark, Clark and Rodas, and in the U.K. by Tuck. Schumann and Schardin obtained similar flash radiographs in Germany in 1941. Birkhoff and Schumann discuss the "angry priority controversy" over the first flash radiograph. X-ray photographs (or flash radiographs) are necessary since ordinary photographs are uninformative due to the smoke and flame associated with the detonation (Walters and Zukas 1989).

Based on the analysis of the flash x-ray data and the partial collapse studies, analytical models of the collapse of a lined conical shaped charge were developed and verified by Birkhoff, et al., Evans, Tuck, and Pugh, et al.

Shaped charge theory continued to develop during the 1950s, boosted by the Korean War. During this time period, tremendous progress was made toward the understanding of the phenomena associated with shaped charge jets. Improved flash x-ray techniques were employed to observe the jet process and analytical models were improved. Efforts were made to improve existing shaped charge liners; to use detonation wave shapers; to provide spin compensation via fluted liners; to provide shaped charge follow-through mechanisms; and to enhance the overall system performance. Slugs from shaped charge firings were recovered and metallographic analyses were performed. Jet temperature effects were examined and the effect of environmental pressure and temperature on shaped charge jet formation and performance was studied. These early publications discussed many of the problems still being studied today .

Starting in the 1950-1960s, significant shaped charge developments were made possible by the perfection of experimental techniques such as high-speed photography and flash radiography. Other improvements resulted from the transition from TNT to more energetic explosives, i.e., from TNT to Comp B to Octol and then to pressed explosives, notably LX-14. Also, alternate modes of initiation (other than point-initiation) and waveshaping techniques have provided warhead design improvements. Other advances stemmed from the development of large computer codes to simulate the collapse, formation, and growth of the jet from a shaped charge liner. Numerical techniques and the advantages and limitations of various computer codes for wave propagation and penetration studies are discussed in detail elsewhere (Walters and Zukas 1989; Zukas 1990). These codes provide for the most part, excellent descriptions of the formation of the jet.

## 3. APPLICATIONS OF SHAPED CHARGES

Shaped charges are extremely useful when an intense, localized force is required for the purpose of piercing a barrier. A primary application is in the military arena including torpedoes, missiles, high explosive anti-tank (HEAT) rounds including hand held (bazooka type) rounds, gun launched rounds (e.g., rifle grenades), cannon launched rounds, and various bombs. The targets are armors, bunkers, concrete or geological fortifications, and vehicles. Attacks against aircraft and spacecraft are possible. Underwater applications (torpedoes) are possible.

The largest known shaped charge was the German MISTEL. The MISTEL (mistletoe) concept used a fighter aircraft mounted piggyback on the top of a large bomber aircraft. The unmanned bomber carried the MISTEL warhead in its nose. The warhead consisted of a 2-meter diameter, wide angle, conical shaped charge. The warhead weighed 3,500 kg with an explosive weight of 1,720 kg. The fighter pilot flew the combination to the target, aimed it, released it, then returned to his base. The Germans developed this device near the end of World War II and most of them were captured intact. The Japanese used a scaled version of the MISTEL, called the SAKURA bomb, for kamikaze attacks against warships.

Zwicky proposed the use of a shaped charge as a method of producing artificial meteorites in 1947. He proposed launching a hypervelocity shaped charge on a V-2 rocket to exceed the earth's escape velocity and thus create an artificial meteorite. Also, the hypervelocity jet particles could be tracked to study hypersonic aerodynamic effects. In addition, the experiment could be designed to allow the jet to impact a heavenly body, such as the moon. A spectroscopic analysis of the impact flashes would reveal the elementary chemical constituents of the moon's surface. Shaped charges were eventually used to simulate meteorites.

Many other specialized shaped charge applications have been pursued by the Departments of Defense of several nations. These specialized designs included confinement or tamping of the explosive fill, varying the

geometry or type of explosive used, altering the mode of initiation, using explosive lenses or more than one type of explosive or an explosive-non-explosive barrier or gap, waveshaping or shaping the detonation wave (usually done to insure a plane wave with a short head height), or varying the standoff distance. Also, significant effects can be achieved by varying the liner material (including the use of non-metals such as glass), varying the liner thickness, increasing the liner diameter, tapering (or causing a gradual wall thickness variation either continuously or discontinuously) or varying the liner geometry. The liner geometry variation may utilize the same basic geometry, e.g., varying the conical apex angle, or may employ a radically different liner configuration. Other useful liner geometries are hemispheres, truncated (from the equator) hemispheres, disc or dish shaped (EFP like) devices, tulips, trumpets, dual angle cones, or a combination of the above such as hemi-cones or tandem devices.

Other applications may use spin compensated liners, especially when associated with spinning warheads. Gun fired projectiles are spun in flight to provide aerodynamic stability. Spin compensation (i.e., causing the jet to spin enough and in the right direction to compensate for the spin of the warhead) may be achieved by metallurgical spin compensation or by the use of fluted liners. Metallurgical spin compensation is achieved by introducing anisotropies or residual stresses into the liner during the fabrication process in order to provide rotation of the jet. Fluted liners contain raised ridges (or panels which are offset with respect to the normal to a radius) on the outside and/or the inside surface of the liner. The flutes allow the jet to form with a given angular momentum to compensate for the rotation of the warhead in flight.

There exists numerous other tales of warhead development, the point being that some of the warhead concepts being pursued today are not original concepts. For example, the tandem warhead concept was first proposed by Tuck in 1943 and patented in 1946 by Precoul of France (Zukas 1990).

Another application of shaped charges is in demolition work. This area has both military and industrial application. Buildings, bridges, and other structures are the common demolition targets. The shaped charge principle is also used in construction work to break, crack, or drill holes in rock. A technique known as mudcapping is sometimes used to break rock and usually utilizes an unlined hollow charge. Shaped charges have also been used in construction as earth movers, in tunneling, or to assist in well drilling.

Shaped charges are also used in tapping steel mill furnaces, as a source of earth waves for geophysical prospecting and seismic exploration, mining (surface or underground), quarrying, in salvage operations, boring holes in demolition work, breaking large rocks, and for hypervelocity impact studies. Other applications occur in submarine blasting, breaking log jams, breaking ice jams, initiating avalanches, timber or tree cutting, the perforation of arctic sea-ice, glacier blasting, ice breaking, hole drilling, post hole digging, and underwater demolition.

Shaped charge liners are not always made of glass or metals, e.g., Naval Proving Ground, describes a shaped charge with a liner made of balsa wood. In fact, liners have assumed a multitude of geometric shapes, and have been made from common and exotic metals, alloys, eutectics, ceramics, plastic, paper, rubber, etc.

Another application of the shaped charge is in the internally coned end of certain detonators. This indented, lined cavity acts to concentrate the effect along the axis. In fact, in 1886, Gustov Bloem patented a shell for detonating caps which resembles a shaped charge with a hemispherical liner. Also, the Munroe Effect is used to engrave or stencil letters and other designs onto metal plates.

The shaped charge has also been employed for assorted peaceful purposes in the petroleum industry (Walters and Zukas 1989; Zukas 1990; Walters 1991). In the oil well industry, large diameter, but extremely short, lined shaped charges are used to penetrate various geological formations to increase the flow of oil. Oil well completion problems present extremely difficult design problems due to the minimal amount of allowable space available in the well, the short standoff distances required, and the hostile environment within the well.

Linear (wedge-shaped, V-shaped or W-shaped) shaped charges are used as cutting charges. They generate a ribbon-shaped jet used to cut metals and other materials. Commercial cutting charges are available from several sources. For cutting charge applications, it is sometimes advantageous to use homemade cutting charges which can be optimized to the particular problem on hand. Cutting charges and hollow charges are also used as explosive separation devices, as bolt cutters, and for other applications. The shaped charge effect is used on systems for separation, deployment, and safety destruct devices in missiles and spacecraft .

Additional applications relating to explosive metal interactions,which require an understanding of the jet formation phenomena, are explosion welding, explosion cladding, or explosion forming of metal parts.

## 4. JET FORMATION CONCEPTS

Many efforts have been made over the years to understand the various modes of jet formation, i.e., formation of jets from conical, hemispherical, and EFP liners. The flow near the collision region in the jet formation process for moderate apex angle conical shaped charge liners, i.e., when the liner material splits into a jet-slug flow, is of special interest.

Walters and Golaski performed a series of experiments that clearly describe the mode of flow separation in the collapse of both conical and hemispherical shaped charge liners. These experiments also confirmed the computer predictions regarding flow separation. The experiments employed bimetallic liners of copper and

nickel to show the differences between the material flow in the two geometries studied. Copper and nickel were chosen because of their identical density and similar behavior under shock loading. Solid bimetallic cylinders of alternate layers of copper and nickel were fabricated by diffusion bonding of the materials under pressure. This technique yields a void-free sample suitable for explosive loading studies. Conical and hemispherical liners were cut from the cylinders that had alternate disks of copper and nickel. A photograph of the stratified, bimetallic conical liner is shown in Figure 4. The liners were cast in 75/25 Octol. Radiographs reveal jets which, while not perfect, were well formed, coherent and representative of copper liners of this type. The charges were fired over water recovery tanks made from large-bore gun barrels and the slugs and larger jet particles were recovered. The recovered particles were metallurgically examined and found to have the stratification predicted in the computer studies. Figure 5 shows the computer simulation of the collapse of the conical liner. Figure 6 is a cross section of the slug recovered from the experiment and Figure 7 shows the longitudinal cross section from a recovered jet particle. The stratified, bimetallic hemispherical liner is shown in Figure 8 and the computer simulation is shown in Figure 9. Figure 10 shows the cross section of a recovered jet particle. The stratification, tubular flow can be clearly recognized and is clearly the same as that shown in the computer simulation.

## 5. COHERENT JET CRITERIA

Walsh et al. (Walters and Zukas 1989) study the compressibility effect in the jet formation process as related to two plates impacting each other obliquely. The symmetric plate collision, as viewed from a moving coordinate system, reduces to a flow field analogous to two impinging streams. Walsh et al. (Walters and Zukas 1989) concluded that jetting always occurs if the fluid is incompressible or if the collision velocity in the moving coordinate system is subsonic. For supersonic flow, jetting always occurs if the collapse angle ($\beta$) is greater than the critical turning angle for an attached oblique shock wave at the collision velocity (called the critical collapse angle, $\beta_c$). Walsh et al. (Walters and Zukas 1989) did not address jet cohesiveness per se since their primary interest was explosive bonding.

In the studies of Chou et al. (Walters and Zukas 1989), jetting criteria for axisymmetric cases are presented along with a measure of jet quality. Chou et al. state the following:

1. For subsonic collisions (or the collision velocity $V < C$, the material bulk speed of sound), a solid coherent jet always forms.

2. For supersonic collisions ($V > C$) jetting occurs if $\beta > \beta_c$, but the jet is not coherent. The angle $\beta_c$ is the maximum angle that an attached shock wave can form at a prescribed supersonic velocity, V.

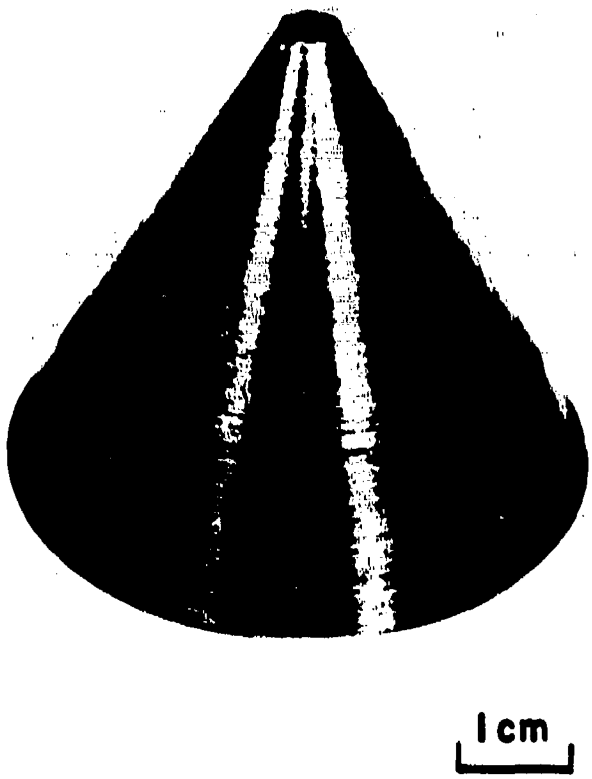



Figure 4. Finish Machined Alternately Layered Copper-Nickel Cone.

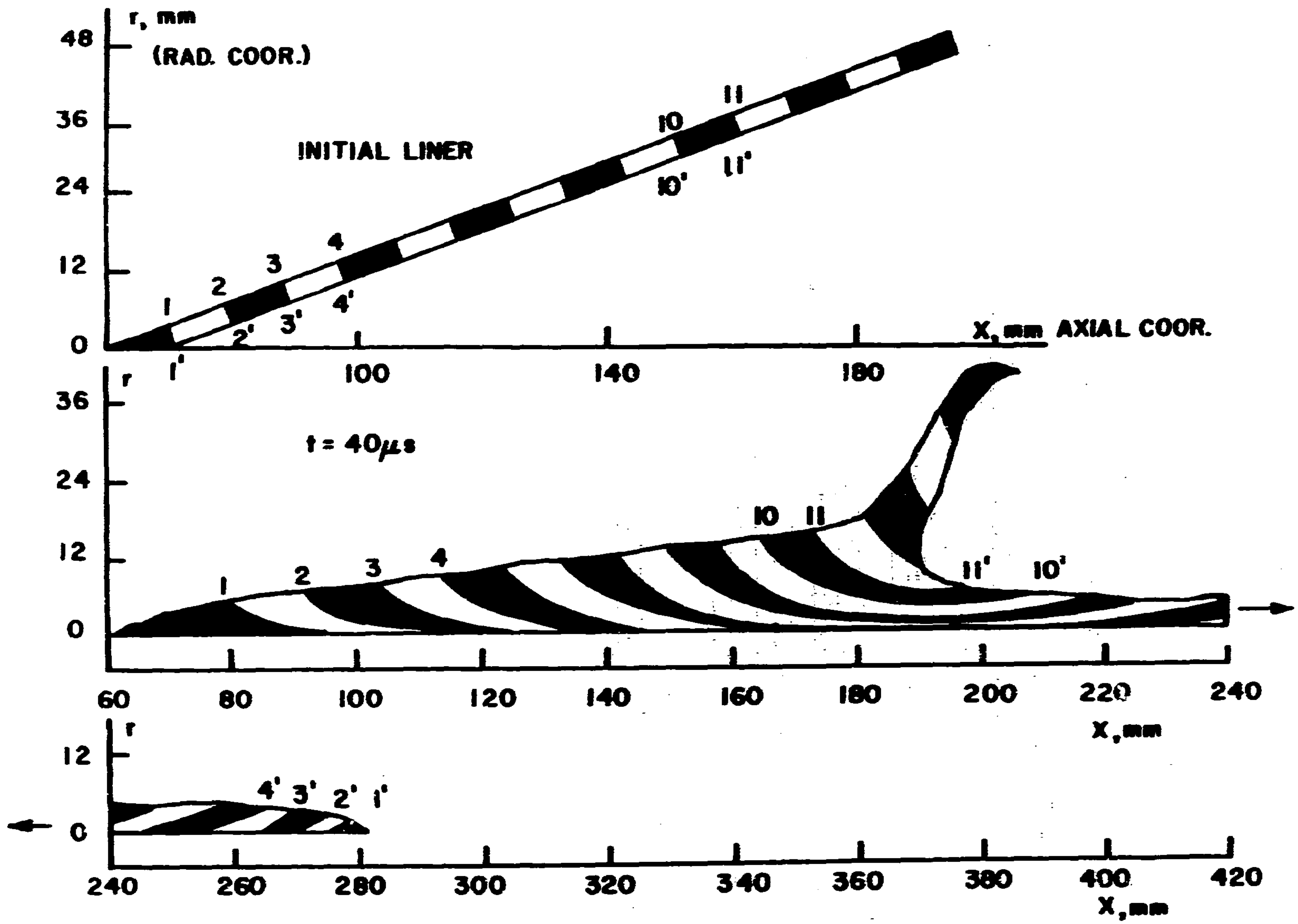
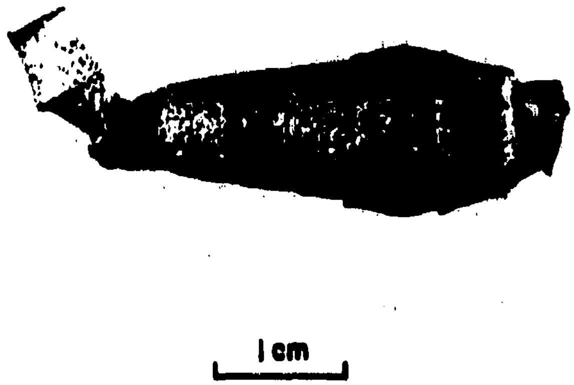



Figure 5. HELP Code Simulation of 42° Conical-Liner Charge, Initial Liner Geometry (Top), Jet and Slug at 40μs (Center and Bottom).




**OUTSIDE SURFACE**

**CROSS SECTION**

Figure 6. Recovered Slug From Alternately Layered Copper-Nickel Cone.

Figure 7. <u>The Cross Section of a Jet Particle Recovered from the Alternately Layered Copper-Nickel Cone</u>.

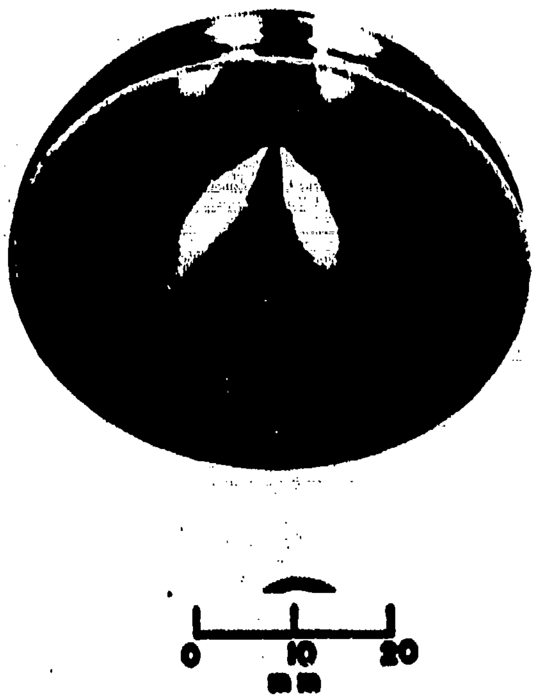



Figure 8. Finish Machined Alternately Layered Copper-Nickel Hemisphere.

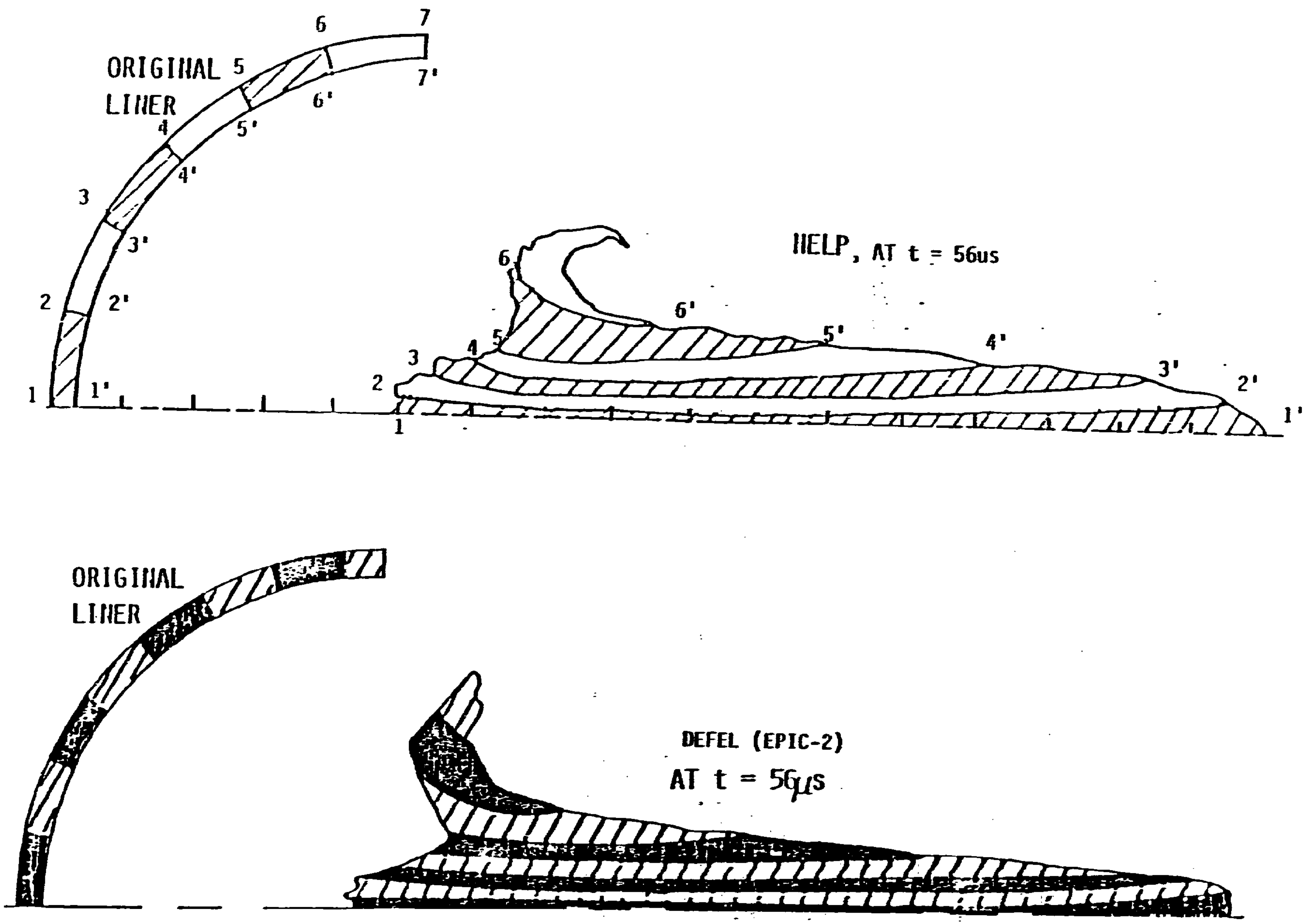



Figure 9. Computer Code (HELP and DEFEL) Simulation of Jet Formation of a Hemispherical Liner Charge.


Figure 10. Cross Section Of One-Half of a Recovered Jet Particle from an Alternately Layered Copper-Nickel Hemispherical Shaped Charge Liner.

3. For supersonic collisions ($V > C$) but $\beta < \beta_C$, a jet will not be formed.

For shaped charge applications, the major criterion for jetting is that the formation process be subsonic. Otherwise, the jet will be incoherent and spread out radially.

The speed of sound referred to is usually taken to be the bulk speed of sound of the material as opposed to a longitudinal or transverse shear speed of sound. The appropriate speed of sound, as well as its exact value under the extreme pressures and temperatures encountered in the formation region, is not well known. Also, the actual flow field is compressible and two-dimensional (at least), and hence, the subsonic collision condition is useful only as a general principle. In practice, it has been observed that the value of the critical Mach number based on the static bulk speed of sound is about 1.2 for conical copper liners. In other words, the liner velocity divided by the bulk speed of sound, that is, the Mach number could be as high as 1.2 and still achieve a cohesive jet for a conical copper liner. A flow velocity of 4.8 km/s (1.23 times the bulk speed of sound of copper) is the calculated flow velocity above which 20° copper liners have been observed to have incoherent jet tips (Walters and Zukas 1989).

The jet-no-jet criterion, or the limiting condition for jet formation, is based on the studies of Cowan and Holtzman, Walsh et al., Chou et al., and Harlow and Pracht (Walters and Zukas 1989). These studies relate to shock formation and critical collapse angles and are also applied to shaped charge jets. (Note that the explosive weld geometry is a two-dimensional [wedge] shaped charge.) El-Sobky (Walters and Zukas 1989) notes that the collision velocity and plate impact velocity should be less than the bulk speed of sound of either welding component. However, Wylie et al. (Walters and Zukas 1989) suggest that the bulk speed of sound may be exceeded by as much as 25% with satisfactory welds. It is interesting that this coincides with the jet-no-jet criterion observed by Harrison and Harrison et al. (Walters and Zukas 1989) for copper jets, that is, Mach number of 1.23.

The calculation of pressure and bulk speed of sound during the collapse and formation of the jet is currently being pursued by several investigators, notably Murphy, Brown et al., and Miller et al. as reported in the recent (1990) 12th International Ballistics Symposium.

## 6. THE JET TEMPERATURE

In a series of publications, von Holle and Trimble (Walters and Zukas 1989) developed a temperature measurement technique for shocked metals based on two-color infrared radiometry. Their results include the application of their method to the residual temperature measurement of thin copper plates shocked in the 30-50 GPa range. Data on the temperature measurements of shaped charge jets in flight are also presented.

From von Holle and Trimble (Walters and Zukas 1989), the temperature of the jet from a 81.3-mm diameter, copper conical liner was measured. The explosive fill was Comp B and an eleven shot average of the jet temperature was 428° C with a standard deviation of 67° C. The jet was fired into a vacuum. Both pointed and rounded apex liners were used in the temperature measurement tests. The pointed apex cone revealed a higher temperature than the rounded apex cone.

Several shots were fired using both rounded and pointed apex cones and both Comp B and Octol explosive fills. Averaging all data from von Holle and Trimble gave a 12-shot average temperature for the Comp B-loaded charges of 441° C with a standard deviation of 80° C. For the Octol-loaded charges, a six-shot average temperature was 521° C with a standard deviation of 40° C.

For the pointed apex conical copper jets, the temperature versus distance from the jet tip was measured. The trend of the data indicated that the jet temperature rises behind the tip then levels off. Also, the jet tip was viewed end-on for an Octol-loaded charge in order to measure the jet temperature during formation. The temperature appeared to decrease at later times after formation.

Also, von Holle and Trimble measured the jet temperature of a 60°- apex angle, 81.3-mm diameter, tin-lead eutectic liner. The liner wall thickness was 2.54 mm and the explosive fill was Comp B. The conical apex was slightly rounded to a 1-mm radius. A four-shot average revealed a jet temperature of 569° C with a standard deviation of 34° C. The tin-lead liner had a jet tip velocity of 6.3 km/s compared to the copper liner jet tip velocity of nearly 8 km/s.

Von Holle and Trimble concluded that the copper jet was solid and the lead-tin jet was liquid in spite of any scatter in the data. The von Holle-Trimble experiments were the first of a kind and represent an excellent approach to a difficult problem, although some uncertainty exists in the recorded data. The explanation of the experimental technique and the interpretation of the data is given in von Holle and Trimble (Walters and Zukas 1989; Zukas 1990).

Walters et al. (Walters and Zukas 1989) performed hydrocode calculations to calculate the temperature gradients in collapsing lead hemispherical liners. The wall thickness of the liner was varied, and free-flight flash radiograph coverage of the jet revealed that the jet quality improves as the wall thickness increases. That is, the jet becomes less fluid, or more solid, in appearance as the wall thickness increases.

The HULL, HELP, and EPIC codes were all used to study the hemispherical liner collapse and formation. Temperature calculations throughout the jet were obtained, and the general temperature

trends were in qualitative agreement with the appearance of the jets from the lead hemispherical liners (i.e., transitions from liquid to solid were revealed). Also, calculations were made for Octol-loaded copper liners which agreed with the temperature measurements of von Holle and Trimble.

Analytical calculations of the shaped charge jet heating were made by Pfeffer and by Racah (1988). The shaped charge jet temperature was induced by liner heating due to the shock wave, liner heating during the collapse process, and jet heating during the elongation process. Racah concluded that most of the jet heating was caused by plastic deformation during the liner collapse and elongation whereas the heating caused by the explosive shock wave was relatively low. Racah quoted the von Holle-Trimble measured temperature rise to be 400° C ± 130° C and his calculated peak temperature rise of 290° C falls within the lower bound of the experimental range. Pfeffer calculated a copper jet temperature rise of 368° C on the jet surface, but Racah disputed the calculations of Pfeffer.

The calculated temperatures were obtained from the initial temperature, the density, the internal energy, and the specific heat of the liner material. The specific heat was assumed to be a constant, which is probably not realistic. Other computational errors would result from lack of data on materials under high-pressure, high-temperature, and high-strain rate conditions, for example, exact constitutive equations and exact equations of state.

Nevertheless, the experimental and theoretical information provided by the preliminary studies cited represent an important first step toward the estimation of the temperature and temperature gradients of a shaped charge jet. Current studies are underway at Los Alamos National Laboratory (LANL), and other laboratories, to obtain the correct material and equation of state models to accurately predict the jet temperature and temperature gradients.

## 7. CONCLUSIONS

The shaped charge concept, oft misunderstood, was explained along with the prevalent dynamics of materials subjected to high pressure, high velocity, high strain, and high-strain rates. In addition, the history and the various and sundry applications of the shaped charge principle were elucidated. Finally, three current areas of shaped charge research namely, jet collapse and formation, coherent jet criteria, and jet temperature calculation were discussed.

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